Patent Application of

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for

Thermionic Vacuum Diode Device with Adjustable Electrodes

Cross-Reference to Related Applications

[1] This is a continuation in part of application of Application No. 09/481,803, filed 31 August 1998, Patent No. 6,720,704, which is a Continuation in Part of Application No. 08/924,910, filed 8 September 1997, abandoned. This application is also related to U.S. Pat. Appl. No. 09/645,997, filed 31 August 1998 as a Continuation in Part of U.S. Pat. Appl. No. 09/645,985, filed 9 February 1998 as a Continuation in Part of U.S. Pat. No. 6,281,514, and assigned to the same assignee as the present invention.

Background of the Invention

[2] The present invention is related to diode devices, in particular, to diode devices in which the separation of the electrodes is set and controlled using piezo-electric, electrostrictive or magnetostrictive positioning elements. These include thermionic converters and generators, photoelectric converters and generators, and vacuum diode heat pumps. It is also related to thermotunnel converters.

[3] One form of thermionic vacuum diode is the thermionic converter. A problem associated with the design of these is the space-charge effect, which is caused by the electrons themselves as they leave the cathode. The emitted electrons have a negative charge that deters the movement of other electrons towards the anode. Theoretically, the formation of the space-charge potential barrier may be prevented in at least two ways: positive ions may be introduced into the cloud of electrons in front of the cathode, or the spacing between the electrodes may be reduced to the order of microns.

[4] The use of positive ions to reduce space charge is not without problems. Although cesium and auxiliary discharge thermionic converters have

been described, they do not have high efficiency, are costly to fabricate, and, particularly in the high-pressure ignited mode, do not have a long life. The technique of introducing a cesium plasma into the electrode space brings with it further disadvantages. These include heat exchange reactions within the plasma during the operation of the device, and the reactivity of the plasma, which can damage the electrodes.

[5] Although Fitzpatrick (U.S. Pat. No. 4,667,126) teaches that "maintenance of such small spacing with high temperatures and heat fluxes is a difficult if not impossible technical challenge", in an article entitled "Demonstration of close-spaced thermionic converters", 28th Intersociety Energy Conversion Engineering Conference, Vol. 1, pages 1573 - 1580, he goes on to disclose a close spaced thermionic energy converter which operates at temperatures of 1100 to 1500 degrees Kelvin at a variety of cesium pressures. Electrodes are maintained at a separation of the order of 10 μm by 3 ceramic spacers mounted on the collector. With electrodes at 1300 and 800 degrees Kelvin, conversion efficiencies of 11.6% were obtained. It utilizes advanced monocrystal materials to achieve reliable operation and long life, and produces a reasonable output power with good efficiency at lower temperatures where typical ignited mode devices would produce no useful power at all. It is, therefore, useful at the bottom end of cascaded thermionic systems, with a very high temperature barium-cesium thermionic converter at the top end.

[6] To operate a converter with a gap spacing of less than 10 μm, the electrode surface must be very flat and smooth, with no deformation larger than about 0.2 μm. This places a limitation on the practical size of electrodes for the emitter and collector, because heat flux through the surfaces causes a differential thermal expansion from one side relative to the other, leading to thermal expansion-caused deformation into a "dome-like" shape. This issue is even more important in high power operation. Although this deformation can be tolerated if the diameter of the electrodes is very small, the devices described by Fitzpatrick have diameters of several centimeters. Another issue is degradation of the in-gap spacers at high emitter temperatures.

[7] Fitzpatrick addresses both these in a later paper, entitled "Close-spaced thermionic converter with active control and heat-pipe isothermal emitters", 31st Intersociety Energy Conversion Engineering Conference, Vol. 2, pages 920 - 927. He proposes a device having a large isothermal emitter, utilizing a heat pipe built into its structure with a

single crystal emitting surface. The proposed device avoids degradation of the in-gap spacers at high emitter temperatures by using active spacing control, utilizing piezo-electric actuators in conjunction with feedback control for continuously adjusting the gap size.

[8] The proposed device, however, is relatively large, expensive and not amenable to mass-production. There remains a need, therefore, for a thermionic generator which is easy to fabricate, inexpensive, reliable, of high efficiency, modular, compact and having an extended life.

[9] Another approach for electron sourcing is disclosed by Kennel (U.S. Pat. No. 5,410,166) who uses a negative electron affinity material such a p-type diamond disposed adjacent a p-n junction in order that electron charge carriers originating in the p-n junction may be caused to flood the p-type diamond and increase its electrical conductivity and also provide a source for high current flow free electrons repelled from the surface of the diamond material. He does not however, teach the application of this approach to power generation or heat pumping applications, but suggests it may be applied to such applications as cathode ray tubes. It is to be noted that the surfaces of the cathode in Kennel's disclosure are not smooth, and the diamond array is typically of 5 - 10 microns in height, which would prevent the anode being brought into close proximity, ie less than 10 microns, with the cathode.

[10] Close-spaced surfaces are disclosed by DiMatteo (U.S. Pat. No. 6,084,173) in an invention for enhancing the generation of carriers in semiconductor devices. In this disclosure, photons emitted from the heated surface are transferred across a small, evacuated gap to the nearby photovoltaic cell, or other semiconductor receiver. DiMatteo does not however teach the emission of electrons across the evacuated gap.

[11] There are many potential applications of an efficient thermionic generator. For example, the alternator of the automobile could be replaced by a thermionic generator using the heat contained in the exhaust gases as a source of energy, which would lead to an increase in the efficiency of the engine. Svensson and Holmlid, in their paper entitled: "TEC as Electric Generator in an Automobile Catalytic Converter" 31st Intersociety Energy Conversion Engineering Conference, Vol. 2, pages 941 - 944, propose the possible use of carbon covered electrodes which become coated with Rydberg matter, resulting in the reduction of the interelectrode distance. They report that such a device might be expected to have an efficiency of 25 - 30% at temperatures of 1500 -1600 degrees Kelvin. To obtain the high temperatures

required, a fuel mixture would be injected into the device. Different configurations are discussed, but it is not clear how such a device would be economically constructed.

[12] Another application is in domestic and industrial heating systems. These need a pump to circulate heated water around the system, which requires a source of power. The control circuitry regulating the temperature of the building being heated also requires power. These could both be supplied by means of a thermionic generator powered by the hot flue gases.

[13] A further application utilizes heat generated by solar radiation. This could either be in space or earth-based solar power stations, or on the roof of buildings to supply or augment the power requirements of the building.

[14] In U.S. Pat. No. 5,994,638 to Edelson, assigned to the same assignee as the present invention, and incorporated herein in its entirety by reference, a thermionic converter having close spaced electrodes is disclosed which is fabricated using micromachining techniques. This device addresses many of the problems described above, particularly those relating to economic fabrication and how to achieve close spaced electrode design. However, in operation, temperature differences between the hot emitter and cooler collector may cause high thermal stresses leading to the shape of the region between the electrodes being altered.

[15] The present invention extends the robustness of Edelson's previous device without detracting from its ease and economy of fabrication by allowing it actively to respond to these high thermal stresses by means of active piezo-electric, electrostrictive or magnetostrictive elements incorporated to produce a micro-electromechanical thermionic converter.

[16] The thermotunnel converter is a means of converting heat into electricity which uses no moving parts. It has characteristics in common with both thermionic and thermoelectric converters. Electron transport occurs via quantum mechanical tunneling between electrodes at different temperatures. This is a quantum mechanical concept whereby an electron is found on the opposite side of a potential energy barrier. This is because a wave determines the probability of where a particle will be, and when that probability wave encounters an energy barrier most of the wave will be reflected back, but a small portion of it will 'leak' into the barrier. If the barrier is small enough, the wave that leaked through will continue on the other side of it. Even though the particle does not have enough energy to get

over the barrier, there is still a small probability that it can 'tunnel' through it.

[17] The thermotunneling converter concept was disclosed in U.S. Patent No. 3,169,200 to Huffman. In a later paper entitled "Preliminary Investigations of a Thermotunnel Converter", [23^{rd} Intersociety Energy Conversion Engineering Conference vol. 1, pp. 573-579 (1988)] Huffman and Haq disclose chemically spaced graphite layers in which cesium is intercalated in highly orientated pyrolitic graphite to form a multiplicity of thermotunneling converters in electrical and thermal series. In addition they teach that the concept of thermotunneling converter was never accomplished because of the impossibility of fabricating devices having electrode spacings of less than 10 μm. The current invention addresses this shortcoming by utilizing one or more piezo-elèctric, electrostrictive or magnetostrictive elements to control the separation of the electrodes so that thermotunneling between them occurs.

[18] A further shortcoming of the devices described by Huffman is thermal conduction between the layers of the converter, which greatly reduces the overall efficiency of these thermotunneling converters.

[19] In U.S. Pat. No. 5,973,259 to Edelson, assigned to the same assignee as the present invention, and incorporated herein by reference, is described a Photoelectric Generator having close spaced electrodes separated by a vacuum. Photons impinging on the emitter cause electrons to be emitted as a consequence of the photoelectric effect. These electrons move to the collector as a result of excess energy from the photon: part of the photon energy is used escaping from the metal and the remainder is conserved as kinetic energy moving the electron. This means that the lower the work function of the emitter, the lower the energy required by the photons to cause electron emission. A greater proportion of photons will therefore cause photo-emission and the electron current will be higher. The collector work function governs how much of this energy is dissipated as heat: up to a point, the lower the collector work function, the more efficient the device. However there is a minimum value for the collector work function: thermionic emission to the collector will become a problem at elevated temperatures if the collector work function is too low.

[20] Collected electrons return via an external circuit to the cathode, thereby powering a load. One or both of the electrodes are formed as a thin film on a transparent material, which permits light to enter the device. A

solar concentrator is not required, and the device operates efficiently at ambient temperature.

[21] In U.S. Pat. No. 6,089,311 to Edelson, assigned to the same assignee as the present invention, incorporated herein in its entirety by reference, a new use for thermionic vacuum diode technology is disclosed wherein a vacuum diode is constructed using very low work function electrodes. A negative potential bias is applied to the cathode relative to the anode, and electrons are emitted. In the process of emission, the electrons carry off kinetic energy, carrying heat away from the cathode and dissipating it at an opposing anode. The resulting heat pump is more efficient than conventional cooling methods, as well as being substantially scaleable over a wide range of applications. Fabrication using conventional techniques is possible.

[22] Piezo-electric worm-type shifting mechanisms, or piezo-electric motors, can move extremely short distances of the order of a single angstrom, while having a stroke of several tens of millimeters.

[23] Scanning Tunneling Microscopes are well known for employing piezo-electric devices to maintain tip distance from a surface to an accuracy of 1 angstrom.

[24] U.S. Pat. No. 4,423,347 to Kleinschmidt et al. discloses a type of electrically actuated positioning element formed of piezo-electric bodies, which may, for example, be used to operate a needle valve.

[25] U.S. Pat. No. 5,351,412 to Furuhata and Hirano discloses a device which provides micro-positioning of the sub-micron order.

[26] U.S. Pat. No. 5,049,775 to Smits discloses an integrated micro-mechanical piezo-electric motor or actuator. This has two parallel cantilever beams coated with a piezo-electric material and attached to a body to be moved at one end, and to a V-shaped foot at the other. By applying an electric field, the foot may be raised, twisted, lowered and straightened, providing movement. An example has a device with cantilever beams measuring 1 x 10 x 200 μm which can move at 1 cm/s.

[27] The above illustrate that piezo-electric elements may be fabricated and used at micron and sub-micron scale and that they are useful for positioning objects with great accuracy. Fitzpatrick takes advantage of these features in his proposed close spaced thermionic converter. He does not teach, however, that micro-mechanical devices such as that disclosed by Smits

may be adapted to form a useful function in positioning the electrodes in a micromachined thermionic vacuum diode.

[28] Razzaghi (U.S. Pat. No. 5,701,043) teaches that some commercially available magnetostrictive materials readily produce strains 10 times higher than that of electroactive materials such as piezo-electric or electrostrictive elements. They are also superior with respect to load, creep, sensitivity to temperature and working temperature range. He discloses a high-resolution actuator using a magnetostrictive material able to achieve displacements with sub-nanometer resolution and a range of about 100 µm.

[29] Visscher (U.S. Pat. No. 5,465,021) disclose an electromechanical displacement device which uses piezo-electric, electrostrictive or magnetostrictive clamping and transport elements.

[30] Takuchi (U.S. Pat. No. 5,592,042) disclose a piezo-electric or electrostrictive actuator of bi-morph or uni-morph type, and teach that it may be useful as a displacement controllable element, an ink jet ejector, a VTR head, a switching element, a relay, a print head, a pump, a fan or blower.

[31] Kondou (U.S. Pat. No. 5,083,056) disclose an improved circuit for controlling a bimorph-type electrostriction actuator.

[32] Hattori (U.S. Pat. No.4,937,489) disclose an electrostrictive actuator for controlling fine angular adjustments of specimens under microscopic scrutiny.

[33] It is known to the art that over a 1 cm distance length, a surface can be polished to a fraction of a micron. However, the art provides no methods for providing surfaces which are flat to the order of tens of angstroms. Additionally, the art provides no methods of making electrodes which match each other's surface features, thus providing 2 surfaces which are flat relative to one another. The present invention discloses and claims such a technique, which allows for very close spacing between electrodes.

[34] "Power Chip" is hereby defined as a device which uses a thermal gradient of any kind to create an electrical power or energy output. Power Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

[35] "Cool Chip" is hereby defined as a device which uses electrical power or energy to pump heat, thereby creating, maintaining, or degrading a

thermal gradient. Cool Chips may accomplish this using thermionics, thermotunneling, or other methods as described in this application.

[36] "Gap Diode" is defined as any diode which employs a gap between the anode and the cathode, or the collector and emitter, and which causes or allows electrons to be transported between the two electrodes, across or through the gap. The gap may or may not have a vacuum between the two electrodes, though Gap Diodes specifically exclude bulk liquids or bulk solids in between the anode and cathode. The Gap Diode may be used for Power Chips or Cool Chips, for devices that are capable of operating as both Power Chips and Cool Chips, or for other diode applications.

[37] Surface features of two facing surfaces of electrodes "matching" each other, means that where one has an indentation, the other has a protrusion and vice versa. Thus, the two surfaces are substantially equidistant from each other throughout their operating range.

Brief Summary of the Invention

[38] The present invention discloses, in one preferred embodiment, a Gap Diode fabricated by micromachining techniques in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Another preferred embodiment is a Gap Diode built and operated by MicroEngineeringMechanicalSystems, or MEMS, and its equivalents, in which the separation of the electrodes may be controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

[39] The present invention further discloses a Gap Diode in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators. Preferred embodiments include Cool Chips, Power Chips, and photoelectric converters. In further embodiments, Gap Diodes may be fabricated using micromachining techniques, and include MicroEngineeringMechanicalSystems, or MEMS versions, or their equivalents, in which the electrode separation is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

[40] In a further embodiment, the present embodiment Gap Diodes in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators, and where the space between the electrodes is filled with an inert gas: according to this embodiment the separation of the electrodes is less than the free mean path of the electrons

in the inert gas. This means that thermal conduction between the electrodes is almost entirely eliminated.

[41] In operation, temperature differences between the emitter or cathode electrode, and the collector or anode electrode, of the Gap Diode may cause high thermal stresses leading to the space between electrodes being altered. These thermal stresses may also cause the electrodes to flex, buckle or otherwise change their shape. The present invention addresses these problems by utilizing a piezo-electric, electrostrictive, or magnetostrictive element to control the separation of the electrodes. Furthermore the present invention discloses utilizing a piezo-electric, electrostrictive, or magnetostrictive element to alter the shape of the electrodes to overcome flexing, buckling or shape-changing thermal stresses.

[42] The present invention further discloses a method for fabricating a pair of electrodes in which any minor variations in the surface of one electrode are replicated in the surface of the other. This permits the electrodes to be spaced in close proximity, and in some applications allows for the actuators to be dispensed with.

[43] A further aspect of the present invention is a method for eliminating thermal conduction between different layers of a device by placing them in sufficiently close proximity that the separation of the layers is less than the free mean path of the electrons in the atmosphere between the layers. This may be achieved by creating the different layers from matching surfaces. This approach may be applied, for example, to the manufacture of other electronic devices, such as multilayer computer architectures, and provides an approach to increasing the packing density on such chips; each layer effectively has its own environment of operation.

[44] A method of selecting materials is disclosed which can be used to compensate for thermal expansion. This method is optimal for use in thermotunneling Power Chips and Cool Chips, and also has uses in especially close-spaced thermionic Power Chips and Cool Chips.

[45] The present invention further discloses the concept of employing electron tunneling in a Cool Chip.

[46] These devices overcome disadvantages of prior art systems such as economy and ease of fabrication and problems introduced by heat distortion at high temperature operation.

[47] The present invention comprises one or more of the following objects and advantages:

[48] It is an object of the present invention to provide Gap Diodes or Power Chips or Cool Chips in which the separation of the electrodes is controlled by piezo-electric, electrostrictive or magnetostrictive actuators.

[49] An advantage of the present invention is that alterations to the spacing of the electrodes which may happen as a consequence of the large temperature difference between the electrodes may be nullified.

[50] A further advantage of the present invention is that a less demanding manufacturing specification is required.

[51] A further advantage of the present invention is that the resulting Gap Diode will be extremely resistant to vibration and shock, as the actuators can rapidly counteract any such stresses.

[52] It is a further object of the present invention to provide Power Chips or Cool Chips or Gap Diodes in which the separation of the electrodes is reduced to micron or sub-micron distances, and is maintained at this small distance through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

[53] An advantage of this invention is that space charge effects are reduced.

[54] Another advantage of this invention is that changes in electrode separation due to thermal changes occurring as the device is operated may be compensated.

[55] It is a further object of the present invention to provide Gap Diodes or Cool Chips or Power Chips in which the separation of the electrodes is small enough to allow electrons to tunnel between cathode and anode, and in which this small separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

[56] An advantage of this invention is that the efficiency of the inter-converter is substantially increased.

[57] An advantage of this invention is that heat energy can be efficiently inter-converted and pumped from one electrode to another.

[58] An advantage of this invention is that a temperature differential can be used to generate electricity.

[59] An advantage of this invention is that a low work function electrode is not required.

[60] An advantage of this invention is that, when it is used to pump heat, it can cool down to 1 degree Kelvin.

[61] It is a further object of the present invention to provide Gap Diodes in which the separation of the electrodes is less than the free mean path of an electron, and in which this small separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

[62] An advantage of this invention is that the space between the electrodes may be filled with an inert gas.

[63] An advantage of this invention is that thermal conduction between the electrodes is substantially reduced, and the efficiency of the device is substantially increased.

[64] It is a still further object of the present invention to provide Gap Diodes fabricated using micromachining techniques in which the separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

[65] An advantage of this invention is that the devices may be constructed inexpensively and reliably.

[66] It is a still further object of the present invention to provide Power Chips and Cool Chips fabricated and operated by MicroEngineeringMechanicalSystems, or MEMS in which the separation between electrodes is maintained through the action of piezo-electric, electrostrictive or magnetostrictive actuators.

[67] An advantage of this invention is that the devices may be constructed cheaply and reliably.

[68] It is a yet further object of the present invention to provide pairs of electrodes in which any minor imperfections in the surface of one are replicated in the surface of the other.

[69] An advantage of this invention is that electrodes may be positioned such that the separation between them is of a very small magnitude.

[70] An advantage of this invention is that a larger surface area can be used for pumping heat, converting heat to electricity, or any other functions of a diode.

[71] An advantage of this invention is that benefits accruing to small spaces, such as tunneling effects, can be maximized.

[72] It is a yet further object of the present invention to provide a method of selection of electrode materials in which the thermal expansion coefficient of the cold side is larger than that of the cold side.

[73] An advantage of this invention is that the temperature difference between the two electrodes can be greatly increased before the electrodes touch each other due to thermal expansion.

Brief Description of the Several Views of the Drawing

[74] Figure **1** is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip showing a piezo-electric actuator supporting an electrode.

[75] Figure **2** is a diagrammatic representation of one embodiment of the electrode configuration of a Gap Diode, Power Chip or Cool Chip, showing piezo-electric actuators at intervals along the under-surface of an electrode.

[76] Figure **3** is a diagrammatic representation of one embodiment of a photoelectric Power Chip with electrode separation controlled by piezo-electric actuators.

[77] Figure **4** is a diagrammatic representation of one embodiment of a device illustrating how heat transfer is facilitated.

[78] Figure **5** is a schematic showing a process for the manufacture of pairs of electrodes which have approximately matching surface details.

Detailed Description of the Invention

[79] The following description describes a number of preferred embodiments of the invention and should not be taken as limiting the invention.

[80] The actuating element is often described as being connected to the collector electrode, however, in some embodiments it could by applied to the emitter electrode instead.

[81] Referring now to Figure **1**, two electrodes **1** and **5** are separated by a region between an emitter and a collector **10** and housed in a housing **15**. Electrode **1** is functionally connected to a piezo-electric actuator **20**. An electric field is applied to the piezo-electric actuator via connecting wires **40** which causes it to expand or contract longitudinally, thereby altering the distance of the region **10** between electrodes **1** and **5**. Electrodes **1** and **5** are connected to a capacitance controller **29** which both modifies the piezo-electric actuator **20**, and can give feedback to a power supply/electrical load **27** to modify the heat pumping action, and generating action, respectively. The electrodes **1** and **5** are connected to power supply/electrical load **27** via connecting wires **40**, which may also be used to connect the electrodes **1** and **5** with capacitance controller **29**.

[82] Referring now to Figure **2**, two electrodes **1** and **5** are separated by a region **10** and housed in a housing **15**. Electrode **1** is attached to a number of piezo-electric actuators **20** at intervals. An electric field is applied to the piezo-electric actuators via connecting wires **40** which causes them to expand or contract longitudinally, thereby altering the longitudinal distance of region **10** between electrodes **1** and **5**. Electrodes **1** and **5** are connected to capacitance controller **29** which both modifies the piezo-electric actuator **20**, and can give feedback to a power supply/electrical load **27** to modify the heat pumping action, and generating action, respectively. The longitudinal distance of region **10** between electrodes **1** and **5** is controlled by applying an electric field to piezo-electric actuators **20**. The capacitance between emitter **1** and collector **5** is measured and controlling circuitry **29** adjusts the field applied to piezo-electric actuators **20** to hold the capacitance, and consequently the distance between the electrodes **10**, at a predetermined fixed value. Alternatively, the controller **29** may be set to maximize the capacitance and thereby minimize the distance **10** between the electrodes. The diagram shown in Figure **2** can be used as a thermionic device and/or as a tunneling device, and can be used to function as a Power Chip and/or as a Cool Chip. Capacitance controller **29** may be composed of multiple elements, and each piezo-electric actuator **20** may receive its own distinct signal, independent from the control of surrounding elements.

[83] If it is used as a thermionic device, then electrodes **1** and **5** are made from, or are coated with, a thermionically emissive material having a work function consistent with the copious emission of electrons at the

temperature of thermal interface **30**. The specific work functions can be determined by calculation, or by consulting the art.

[84] When functioning as a Cool Chip, electrons emitted from emitter **1** move across an evacuated space **10** to a collector **5**, where they release their kinetic energy as thermal energy which is conducted away from collector **5** through housing **15** to thermal interface **35**, which is, in this case, hotter than thermal interface **30** which the electron emission serves to cool.

[85] When functioning as a Power Chip, electrons emitted from emitter **1** move across an evacuated space **10** to a collector **5**, where they release their kinetic energy as thermal energy which is conducted away from collector **5** through housing **15** to thermal interface **35**, and a current is generated for electrical load **27**. The feedback loop from the capacitance controller **29** to the piezo-electric actuators **20** allows for the device to adjust for varying conditions, including vibration, shock, and thermal expansion.

[86] When functioning as a tunneling Gap Diode, as one side of the device becomes hot and its components expand, the distance between the electrodes can be maintained at a fixed distance with the feedback loop between capacitance controller **29** and piezo-electric actuators **20**. Provided the surface of emitter **1** and collector **5** are made sufficiently smooth (or, as discussed below, matching one another) that emitter **1** may be moved into such close proximity to collector **5** that quantum tunneling between the electrodes occurs. As mentioned above, this device can be used as a Gap Diode, a Power Chip, or a Cool Chip. Under these conditions, it is not necessary that region **10** should be evacuated. When the gap distance between the electrodes is in the order of tens of angstroms, thermal conduction through a gas is considerably lessened. In all tunneling embodiments disclosed in this application, this advantage is noted, especially for applications where thermal conduction is a concern, such as Power Chips and Cool Chips. Hence the region **10** is in some embodiments filled with an inert gas.

[87] When functioning as a diode which is not designed to facilitate heat flow, thermal interface **30** and thermal interface **35**, are not necessary, and the resulting device could be integrated into, and used for ordinary diode applications.

[88] It is to be understood that the term "evacuated" signifies the substantial removal of the atmosphere between the electrodes, but does not preclude the presence of atoms such as cesium.

[89] Referring now to Figure **3**, which shows in a diagrammatic form a thermal interface **35**, electrical connectors **40**, and electrical load/power supply **27** for a photoelectric generator embodiment of the device shown in Figure **2**. For the sake of clarity, the controlling circuitry comprising connecting wires **40**, and capacitance controller **29**, and additional connecting wires **40** shown in Figure **2** has been omitted. A light beam **70** passes through housing **15** and impinges on an emitter **1**. Emitter **1** is made from, or is coated with, a photoelectrically emissive material having a work function consistent with the copious emission of electrons at the wavelengths of light beam **70**. Electrons emitted from emitter **1** move across an evacuated space **10** to a collector **5**, where they release their kinetic energy as thermal energy which is conducted away from collector **5** through piezo-electric actuators **20** and housing **15** to thermal interface **35**. The electrons return to emitter **1** by means of external circuit **40** thereby powering electrical load/power supply **27**. The spacing of region **10** between electrodes **1** and **5** is controlled as described above (see Figure **2**). This means that as the device becomes hot and its components expand, the distance between the electrodes can be maintained at a fixed distance. Provided the surface of emitter **1** and collector **5** are made sufficiently smooth, the collector **5** may be moved into such close proximity to emitter **1** that quantum tunneling between the electrodes occurs. Under these conditions, it is not necessary that region **10** should be evacuated, and the device operates as a tunneling Power Chip. It should be noted that a photoelectric Power Chip may use a temperature differential, by collecting some of the solar energy in heat form. In this embodiment, the device would function as the Power Chip in Figure **2**, the only difference being that the heat energy provided would be solar in origin. The device in Figure **3** may alternatively be primarily photoelectric, where direct photon-electron contact results in the electron either topping the work-function barrier and emitting thermionically, or, in the tunneling version where the incidenting photon may cause the electron to tunnel. The device may also be a combination of the above, providing any combination of thermionic emission caused by solar heat, thermionic emission caused by direct photoelectric effects, thermotunneling from solar heat, or tunneling emission caused by direct photoelectric effects.

[90] Referring now to Figure **4**, which shows a preferred embodiment for facilitating heat transfer between a thermal interface **30** and an electrode **1**, corrugated tubes **80**, preferably fabricated from stainless steel, and form part of the structure between electrode **1** and thermal interface **30**. These tubes may be positioned with many variations, and act to allow for the movement of

the positioning elements **20** and of the electrode **1** whilst maintaining support, or containment, etc., for the device, by being able to be stretched and/or compressed longitudinally. In some embodiments, corrugated tubes **80** may form the walls of a depository of a metal powder **82**, preferably aluminum powder with a grain size of 3-5 microns. More metal powder **82** would be used to receive heat transferred to the collector electrode **1**, but the surroundings of the metal powder would be made smaller as the positioning elements **20** would cause the electrode **1** to move toward the thermal interface **30**. Hence the use of an expandable depository, made from corrugated tubing **80**. Corrugated tubes **80** may also enclose the entire device, to allow for movement, as well as individual piezo-electric actuators **20**.

[91] In the devices disclosed above, use is made of actuators for accurate separation between the electrodes of any tunneling Power Chip or tunneling Cool Chip, and the actuators are able to compensate for vibration and thermal stresses. In further embodiments of the present invention, it is envisaged that the need for active actuators may be dispensed with if the device is to be used in a low vibration environment or where high thermal stresses may be avoided. In these embodiments, the separation of the electrodes is set by non-active spacer elements during the manufacturing process, and the actuators, the capacitance loop and power supply shown in Figures **1** - **3** may all be dispensed with.

[92] For currently available materials, a device having electrodes of the order of 1 x 1 cm, surface irregularities are likely to be such that electrode spacing can be no closer than 0.1 to 1.0 μm, which is not sufficiently close for quantum tunneling to occur. However for smaller electrodes of the order of 0.05 x 0.05 cm, surface irregularities will be sufficiently small to allow the electrodes to be moved to a separation of 5 nm or less, which is sufficiently close for quantum tunneling to occur. It is likely that continued developments in electrodes having smoother surfaces will eventually allow large (1 x 1 cm) electrodes to be brought into close proximity so that electron tunneling may occur. One such approach is illustrated and disclosed in Figure **5**, which describes in schematic form a method for producing pairs of electrodes having substantially smooth surfaces in which any topographical features in one are matched in the other. The method involves a first step **100** in which a polished monocrystal of material **102** is provided. This forms one of the pair of electrodes. Material **102** may also be polished tungsten, or other materials. In a step **110** a thin layer of

a second material **112**, is deposited onto the surface of the material **102**. This layer is sufficiently thin so that the shape of the polished surface **102** is repeated with high accuracy. A thin layer of a third material **122** is deposited on layer **112** in a step **120**, and in a step **130** another layer is grown electrochemically to form a layer **132**. This forms the second electrode. In one preferred embodiment, second material **112** has a melting temperature approximately 0.8 that of first material **102** and third material **122**. In a particularly preferred embodiment, second material **112** is lead and third material **122** is aluminum. In a step **140** the composite formed in steps **100** to **130** is heated up to a temperature greater than the melting temperature of layer **112** but which is lower than the melting temperature of layers **102** and **132**. In a particularly preferred embodiment where second material **112** is lead and third material **122** is aluminum, the composite is heated to about 800 degrees Kelvin. As layer **112** melts, layers **102** and **132** are drawn apart, and layer **112** is allowed to evaporate completely. In another preferred embodiment, layer **112** may be removed by introducing a solvent which dissolves it, or by introducing a reactive solution which causes the material to dissolve. This leaves two electrodes **102** and **132** whose surfaces replicate each other. This means that they may be positioned in very close proximity, as is required, for example, for the thermotunnel Power Chip and Cool Chip. In a variation of the method shown in Figure **3**, piezo-electric actuators **20** may be attached to one or both of the electrodes **102** and **132** and used to draw the two apart as the intervening layer **112** melts. This ensures that the two electrodes **102** and **132** are then in the correct orientation to be moved back into close juxtaposition to each other by the piezo-electric actuators.

[93] When considering a Gap Diode wherein the two electrodes are close enough to one another to allow for electron tunneling to occur, thermal expansion considerations are quite important. If thermal expansion is not taken into account, then the two electrodes could touch, causing the device to fail. The present invention discloses that if the cold side of the Gap Diode has a thermal expansion coefficient larger than that of the hot side, then the risk of touching is minimized. A preferred embodiment for this selection process, depending on the design temperature ratios of the device, is that the cold side should have a thermal expansion coefficient which is a multiple of the hot side. Specific embodiments include the use of aluminum on the cold side and titanium on the hot side. The thermal expansion coefficient of aluminum is 6 times that of titanium, and it is disclosed that these two materials form the electrodes, when combined with the electrode matching

invention shown in Figure 5, and will tolerate a difference in temperature between the two sides of up to 500 degrees Kelvin.

[94] In other heat pumping devices that have been described in the art, for example in thermoelectric devices, a major problem is the back flow of heat due to the inability of providing an insulator between the two sides of the device. A particular advantage of the present invention is that the gap between the electrodes is evacuated, thus providing a region of high thermal insulation with good electrical conductance. In a further embodiment, the space between the electrodes may be filled with an inert gas: according to this embodiment the separation of the electrodes is less than the free mean path of the electrons in the inert gas. This means that thermal conduction between the electrodes is almost entirely eliminated. A further aspect of the present invention is a method for eliminating thermal conduction between different layers of a device by placing them in sufficiently close proximity that the separation of the layers is less than the free mean path of the electrons in the atmosphere between the layers. This may be achieved by creating the different layers from matching surfaces. This approach may be applied, for example, to the manufacture of other electronic devices, such as multilayer computer architectures, and provides an approach to increasing the packing density on such chips; each layer effectively has its own environment of operation.

[95] The essence of the present invention are Power Chips and Cool Chips, utilizing a Gap Diode, in which the separation of the electrodes is set and controlled using piezo-electric, electrostrictive or magnetostrictive or other electroactive positioning elements.

[96] Included in this invention is a method for constructing electrodes with matching topologies, the use of thermotunneling to produce a cooling effect, the use of solar energy as the motive energy for Power Chips, the use of small, and angstrom-scale gaps for insulation.

[97] Although the above specification contains many specificities, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention.

[98] For example, the piezo-electric, electrostrictive or magnetostrictive actuators could be used to position either or both electrodes.

[99] Such actuators, which this invention believes are necessary for accurate separation between the electrodes of any tunneling Power Chip or tunneling Cool Chip, do not need to be active once the device has been manufactured. For small temperature variations, it is conceivable that the capacitance loop and power supply for the actuators themselves will not be necessary, and the electrodes can be locked into place in the manufacturing or packaging process. Thus, in operation the actuators would not be necessary, as the gap would not be compromised with smaller temperature fluctuations.

[100] In the above specification, capacitance is used to measure the distance between the electrodes. Other methods known in the art may be used, including measuring the tunneling current and optical interferometry. The generated current produced by a thermionic, thermotunneling or photoelectric Power Chip may also be measured to assess the separation of the electrodes. Other properties which may be measured include heat, for example the temperature of one or both of the electrodes may be used to initiate programmed actuation of the piezo-electric, electrostrictive or magnetostrictive elements. The position of the electrodes may also be set according to the length of time the device has been in operation. Thus it may be envisaged that the electrodes are set at a certain distance when the device is first turned on, and then the positioning of the electrodes is adjusted after certain predetermined time intervals.

[101] In addition, if the inter-converters are constructed using micro-machining techniques, the controlling circuitry for the separation of the electrodes may be deposited on the surface of the wafer next to the piezo-electric, electrostrictive or magnetostrictive actuators.

[102] Although no specific construction approaches have been described, the devices of the invention may be constructed as MicroElectroMechanicalSystems(MEMS) devices using micro-machining of an appropriate substrate. Integrated circuit techniques and very large scale integration techniques for forming electrode surfaces on an appropriate substrate may also be used to fabricate the devices. Other approaches useful in the construction of these devices include vapor deposition, fluid deposition, electrolytic deposition, printing, silk screen printing, airbrushing, and solution plating.

[103] Substrates which may be used in the construction of these devices are well known to the art and include silicon, silica, glass, metals, and quartz.

[104] Additionally, the active control elements may be pulsed, which will generate AC power output when the device is used as a power generator. The pulsing speeds of piezo-electric actuators are well within the requirements necessary for standard alternating voltage outputs.